Design of Interior Permanent Magnet Machines for Hybrid Electric Vehicles

S. Stanton – Technical Director
Z. Tang – Application Engineer, Detroit
Ansoft Corporation

Acknowledgements:
William Cai
Remy International
Stator Lamination and Winding – 2004 Toyota Prius

Power = 50 kW
Bus Voltage = 200 V
Locked Rotor:
Torque = 350 N/m.
Current = 250 Amps.
Speed ~ 3600 rpm (up to 6000 rpm).
Rotor Lamination – 2004 Toyota Prius

Groove for Permanent Magnet

Q Axis

D Axis
2D Structure

Actual Prius Motor

3D Structures

More Complex Design: Stacked PM Rotors with Offset
Objectives

• Analytical vs. FEA Approach
• Proposed Method
  – Geometry creation
  – Reduced FEA modeling techniques
  – Distributed computing
  – Equivalent Circuit Model
• Complete system analysis

*Basis: 2004 Prius IPM motor*
Analytical Method

- Based off of $X_d$ and $X_q$
- Non-Linear permeability is needed

\[
\begin{bmatrix}
X_d & R_l \\
-R_l & X_q
\end{bmatrix}
\begin{bmatrix}
I_d \\
I_q
\end{bmatrix}
= \begin{bmatrix}
U \cos \theta - E_0 \\
-U \sin \theta
\end{bmatrix}
\]

- How to accurately take into account for local saturation?
Transient FEA

- Method of choice
- Dynamic effects
- Voltage source

FEA is the only method to accurately account for local saturation.
Transient FEA

- Time consuming when analyzing the full operating spectrum of the load angle
- During design phase, many topologies are considered

Speed = 3000 rpm
\( \delta = 20 \) degree
Trade Offs for IPM Analysis

• Analytical
  – Fast
  – Calculation of Local Saturation is Challenging

• Transient FEA
  – Accurate
  – Time consuming
Proposed Solution

• Equivalent Circuit Model
  – Static FEA Solutions
  – System Simulator
• Reduced modeling techniques
• Distributed computing

*Ideal during the design phase of 2D & 3D structures*
Geometry Creation – User Defined Primitives (UDP)
# Geometry Creation – User Defined Primitives (UDP)

![Properties: IPMCore - MaxwellDesign1 - 3D Modeler](image)

<table>
<thead>
<tr>
<th>Name</th>
<th>Value</th>
<th>Evaluated...</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>DiaGap</td>
<td>Rotor_OD</td>
<td>100mm</td>
<td>Core diameter on gap side, or outer diameter</td>
</tr>
<tr>
<td>DiaYoke</td>
<td>Rotor_ID</td>
<td>20mm</td>
<td>Core diameter on yoke side, or inner diameter</td>
</tr>
<tr>
<td>Length</td>
<td>Length</td>
<td>50mm</td>
<td>Core length</td>
</tr>
<tr>
<td>Poles</td>
<td>Poles</td>
<td>4</td>
<td>Number of poles</td>
</tr>
<tr>
<td>PoleType</td>
<td></td>
<td>3</td>
<td>Pole type: 1 to 3.</td>
</tr>
<tr>
<td>D1</td>
<td>Duct_LimD</td>
<td>97mm</td>
<td>Limited diameter of PM ducts</td>
</tr>
<tr>
<td>D2</td>
<td>Duct_Width</td>
<td>3mm</td>
<td>Bottom width for separate or flat-bottom duct</td>
</tr>
<tr>
<td>O2</td>
<td>Duct_Shift_D</td>
<td>20mm</td>
<td>Distance from duct bottom to shaft surface</td>
</tr>
<tr>
<td>B1</td>
<td>Duct_Thickness</td>
<td>4mm</td>
<td>Duct thickness</td>
</tr>
<tr>
<td>Rib</td>
<td>Rib_Width</td>
<td>17mm</td>
<td>Rib width</td>
</tr>
<tr>
<td>HRib</td>
<td>Rib_Height</td>
<td>0mm</td>
<td>Rib height</td>
</tr>
<tr>
<td>DminMg</td>
<td>Mag_MinD</td>
<td>5mm</td>
<td>Minimum distance between side magnets</td>
</tr>
<tr>
<td>ThickMg</td>
<td>Mag_Thickness</td>
<td>4mm</td>
<td>Magnet thickness</td>
</tr>
<tr>
<td>WidthMg</td>
<td>Mag_Width</td>
<td>40mm</td>
<td>Total width of all magnet per pole</td>
</tr>
<tr>
<td>InfoCore</td>
<td></td>
<td>2</td>
<td>0: core only; 1: all magnets; 2: all ducts.</td>
</tr>
</tbody>
</table>

[OK]
UDP for Arbitrary Winding Configurations

Concentric winding

Double-layer lap winding

Lap winding with coil pitch=1

DC winding

ClawPoleCore
ConCoil
DCMCore
DiskCoil
DiskPMCore
DiskSlotCore
DoubleCage

IPMCore
LapCoil
LinearMCORE
PMCore
PMDamperCore
RacetrackSlotCore
SalientPoleCore
SlotCore
SquirrelCage
SRMCore
SynRMCore
TransCoil
TransCore
UnivMCORE
VentSlotCore
WaveCoil

LeadingInsight
Application Workshops for High-Performance Design
ECE Method 1

Create a State Space type model from a magnetostatic FEA parametric solution

- Input Variables: IA, IB, IC
- Output Parameters:
  - La, Lb, Lc
  - \( \lambda a, \lambda b, \lambda c \)
  - Torque
System Representation

Where:

\[ \lambda = LI + \lambda_m \]

\[ V = \frac{d\lambda}{dt} \]
ECE Method 1

- All possible combinations of input variables
- Sweep Three Phase currents
  - IA, IB, IC: Sweep +/- Peak: 5-9 steps
  - Rotor Angle: 0-90 deg: 31-61 steps
- Total number of solution:
  - \(5 \times 5 \times 5 \times 31 = 3875\) ... minimum
  - \(9 \times 9 \times 9 \times 61 = 44469\) ... higher fidelity

<table>
<thead>
<tr>
<th>Theta</th>
<th>PhA</th>
<th>PhB</th>
<th>PhC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0deg</td>
<td>-18000</td>
<td>-18000</td>
</tr>
<tr>
<td>2</td>
<td>0deg</td>
<td>-18000</td>
<td>-18000</td>
</tr>
<tr>
<td>3</td>
<td>0deg</td>
<td>-18000</td>
<td>-18000</td>
</tr>
</tbody>
</table>
ECE Method 1

• All possible combinations of input variables
• Sweep Three Phase currents
  • IA, IB, IC: Sweep +/- Peak: 5-9 steps
  • Rotor Angle: 0-90 deg: 31-61 steps
• Total number of solution:
  • $5 \times 5 \times 5 \times 31 = 3875$ ... minimum
  • $9 \times 9 \times 9 \times 61 = 44469$ ... higher fidelity

2D ~1 minute per solution: 2.5 – 31 days
3D ~30 minutes per solution: 81 – 926 days
Proposed Method

• Assume Wye connected winding
  • $IA = Im \cdot \cos(\varpi \cdot \text{PolePairs} - \beta)$
  • $IB = Im \cdot \cos(\varpi \cdot \text{PolePairs} - \beta - 120)$
  • $IC = Im \cdot \cos(\varpi \cdot \text{PolePairs} - \beta - 240)$
  • Let $\phi = \varpi \cdot \text{PolePairs} - \beta$

• Independent  • Dependent
Proposed Method, Full Sweep

- Im from 0 to Imax: 4-9 steps
- Beta from 0 to 360 deg: 12 steps
- Rotor Angle: 0-90 deg: 31-61 steps
- Total number of solutions:
  - \(4 \times 12 \times 31 = 1488\) ... Compared to 3875
  - \(9 \times 12 \times 61 = 6588\) ... Compared to 44469

Can further be improved for rapid design
Periodic Flux Linkage

Waveform can be reconstructed from 15 deg
Periodic Flux Linkage

Waveform can be reconstructed from 15 deg
Periodic Torque Ripple

Waveform can be reconstructed from 15 deg
The Power of Scripting

Flux Linkage vs. Rotor Position

Flux Linkage (Wb)

Rotor Position (mech. deg.)
# The Power of Scripting

## Flux Linkage vs. Rotor Position

<table>
<thead>
<tr>
<th>Torque</th>
<th>Flux A</th>
<th>Flux B</th>
<th>Flux C</th>
</tr>
</thead>
<tbody>
<tr>
<td>-3.73E-03</td>
<td>-4.81E-05</td>
<td>2.75E-02</td>
<td>-2.74E-02</td>
</tr>
<tr>
<td>1.67E+00</td>
<td>-3.31E-03</td>
<td>2.91E-02</td>
<td>-2.58E-02</td>
</tr>
<tr>
<td>-4.81E+00</td>
<td>-6.09E-03</td>
<td>3.03E-02</td>
<td>-2.42E-02</td>
</tr>
<tr>
<td>-1.99E+01</td>
<td>-8.74E-03</td>
<td>3.09E-02</td>
<td>-2.20E-02</td>
</tr>
<tr>
<td>-2.22E+01</td>
<td>-1.20E-02</td>
<td>3.06E-02</td>
<td>-1.88E-02</td>
</tr>
<tr>
<td>-1.88E+01</td>
<td>-1.53E-02</td>
<td>3.07E-02</td>
<td>-1.57E-02</td>
</tr>
<tr>
<td>-1.56E+01</td>
<td>-1.85E-02</td>
<td>3.08E-02</td>
<td>-1.24E-02</td>
</tr>
<tr>
<td>-1.25E+01</td>
<td>-2.13E-02</td>
<td>3.05E-02</td>
<td>-9.27E-03</td>
</tr>
<tr>
<td>-2.41E+01</td>
<td>-2.37E-02</td>
<td>2.99E-02</td>
<td>-6.26E-03</td>
</tr>
<tr>
<td>-2.27E+01</td>
<td>-2.53E-02</td>
<td>2.85E-02</td>
<td>-3.21E-03</td>
</tr>
</tbody>
</table>

*markers indicate specific conditions.*

---

**VB Script**

**Java Script**

**Excel**
User Defined Simploter Models

<table>
<thead>
<tr>
<th>Name</th>
<th>I/O</th>
<th>Type</th>
<th>Extrapolate</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTheta</td>
<td>Input</td>
<td>Parameter</td>
<td></td>
</tr>
<tr>
<td>Im</td>
<td>Input</td>
<td></td>
<td></td>
</tr>
<tr>
<td>beta</td>
<td>Input</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Torque</td>
<td>Output</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L_AA</td>
<td>Output</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L_BB</td>
<td>Output</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L_CC</td>
<td>Output</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Use Bezier Interpolation

Im_IN
beta_IN
TTheta_IN
FL_PMA_OUT
FL_PMB_OUT
FL_PMC_OUT
Torque_OUT
Optimized Input Variations

• Im from 0 to Imax : 4-9 steps
• Beta from 0 to 330 deg: 12 steps
• Rotor angle: 0 to 12/13.5 deg: 5-10 steps
• Total number of solutions:
  • 4 * 12 * 5 = 240 ... Compared to 1488
  • 9 * 12 * 10 = 1080 ... Compared to 6588

Good for rapid design using DSO
Maxwell 3D DSO Setup

Each Design has 72 variations for a total 720 total variations

Just click on Analyze All!
DSO – Distributed Solve Option

**Computation Characteristics**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CPU time</td>
<td>622 hours 10 min</td>
</tr>
<tr>
<td>Real time</td>
<td>66 hours 40 min</td>
</tr>
<tr>
<td>Speed-up factor</td>
<td>9.3</td>
</tr>
<tr>
<td>Average mesh size</td>
<td>79,000 elements</td>
</tr>
</tbody>
</table>

Number of Nodes: 10  
CPU type: Intel Dual Processors 2.8 GHz, 2 Gig RAM  
OS: Windows XP
Simplorer ECE Circuit

\[ V_{DC} \cos \left( PP \cdot (\text{Rotor} \cdot \text{PHI}/12) - \phi \right) \]

\[ V_{DC} \cos \left( PP \cdot (\text{Rotor} \cdot \text{PHI}/12) - 2\cdot \pi/3 - \phi \right) \]

\[ V_{DC} \cos \left( PP \cdot (\text{Rotor} \cdot \text{PHI}/12) - 4\cdot \pi/3 - \phi \right) \]

ICA:

- Turns := 72
- phi := delta \cdot \pi / 180
- period := 1/freq
- speed_rpm := 6000
- freq := speed_rpm \cdot PP^2 / 120

Torque

\[ \text{Torque.OUT} \]

Phase Current

\[ \text{RA . I} \quad \text{RB . I} \quad \text{RC . I} \]

Torque

IPM_SM.Torque_OUT
Simplorer ECE Circuit

**macro model**

\[ \text{Im} \]
\[ \beta \]

\[ A \quad B \quad C \]

\[ \text{Im} \quad \beta \]

**Equations**

\[ \text{EQU} \]

\[ I_{xa} := IA.I \]
\[ I_{xb} := IB.I \times \cos(2\pi/3) \]
\[ I_{xc} := IC.I \times \cos(4\pi/3) \]
\[ I_{x} := I_{xa} + I_{xb} + I_{xc} \]
\[ I_{ya} := 0 \]
\[ I_{yb} := IB.I \times \sin(2\pi/3) \]
\[ I_{yc} := IC.I \times \sin(4\pi/3) \]
\[ I_{y} := I_{ya} + I_{yb} + I_{yc} \]

\[ \text{Im} := \sqrt{(I_{x}^2 + I_{y}^2)} \times \text{Turns} / 1.5 \]
\[ \beta := \left( \text{atan2} \left( I_{x}, I_{y} \right) \right) \times 180/\pi \]
Line to Line Back EMF

Simulated
- Tran. FEA
- Equiv. Ckt.

Measured:
250 V/div
Back EMF vs. Speed

2% < Error < 8% • Computation Time

- Transient 2D FEA: ~4 Hours
- Equivalent Circuit Method 2D: 10 min
Sweep Load Angle;
Speed Held Constant at 3000 rpm

Solution Time: 1 Hour
Future Work: Complete System Analysis
Conclusions

• New Methodology
  – Reduced Modeling Techniques
    • $I_a, I_b, I_c, \Theta \rightarrow I_m, \Theta, \beta$
  – Distributed Processing
• FEA during Design Phase: Rapid Design
• Very Good Accuracy
• Same Methodology for other Motor Types
References

• Report on Toyota/Prius Motor Torque Capability, Torque Property, No-Load Back EMF, and Mechanical Losses,
  – J. S. Hsu, Ph.D., C. W. Ayers, C. L. Coomer, R. H. Wiles
  – Oak Ridge National Laboratory

• Report on Toyota/Prius Motor Design and manufacturing Assessment
  – J. S. Hsu, C. W. Ayers, C. L. Coomer
  – Oak Ridge National Laboratory

• Evaluation of 2004 Toyota Prius Hybrid Electric Drive System Interim Report
  – C. W. Ayers, J. S. Hsu, L. D. Marlino, C. W. Miller, G. W. Ott, Jr., C. B. Oland
  – Oak Ridge National Laboratory